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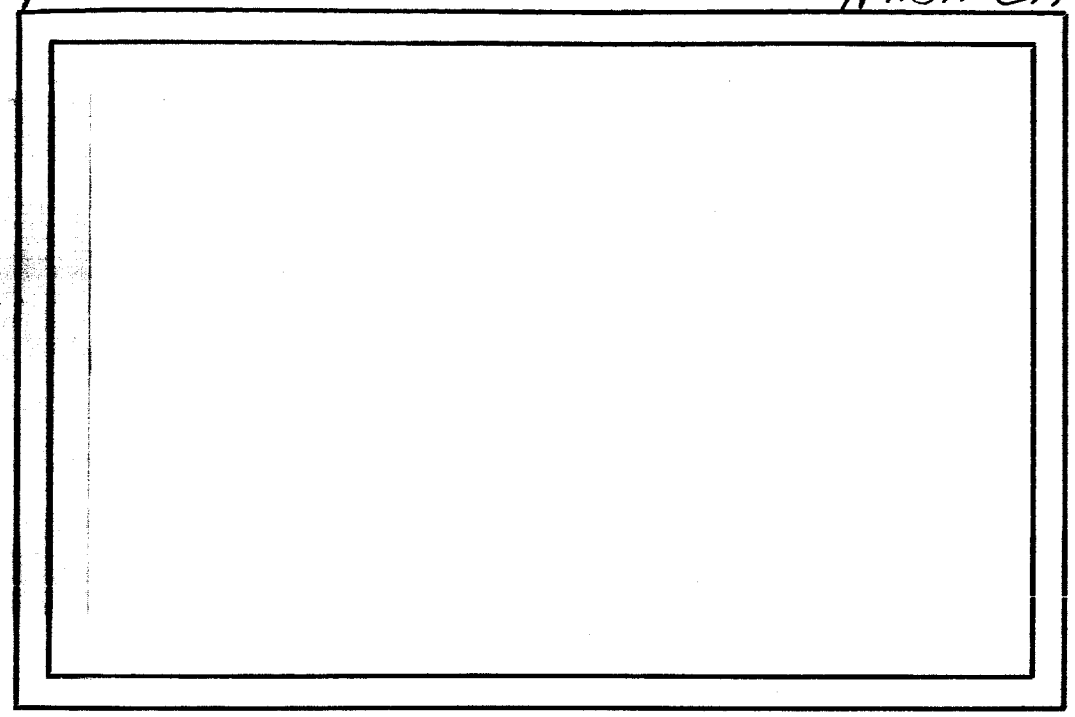

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The Spectrum and Composition of High Energy Cosmic Rays[+]

by

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March, 1964

Physics Department Technical Report No. 368

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Recent experimental results are beginning to supply the fine detail necessary to distinguish between alternative theories of the origins of cosmic rays. This letter is intended to compare these results with predictions of a diffusion model for the propagation of cosmic rays and to suggest possible future observations.

Linsley[1] has suggested that the energy spectrum of cosmic rays steepens in the range $10^{15}eV < E < 10^{17}eV$ but becomes flatter at still higher energies. He has also indicated that the primary particles at energies above $10^{17}eV$ are almost all protons[2]. In the range between $10^{15}eV$ and $10^{17}eV$ the composition of primaries is less certain. Zatsepin and his collaborators[3] report that the composition seems to be essentially unchanged from lower energies, but McCusker[4] suggests a marked shift to heavier nuclei in that range.

This letter explores the consequences of a model in which particles observed below approximately $10^{17}eV$ are assumed to originate in supernovae within the spiral arms of our galaxy and those at higher energies come from extragalactic sources[5]. It assumes that cosmic rays diffuse throughout

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space as suggested by Fermi[6], and amplified by Morrison[7] and many others. However, they do not have time to accelerate significantly in galactic and extragalactic space.

Particles below 10^{15} eV are taken as diffusing through the spiral arms with a scattering mean free path of approximately 10 light years. After approximately 10^5 years they leak into the galactic halo where they diffuse with a longer effective mean free path. This is of the order of 100 light years, and the resultant lifetime of such particles before they leak from the halo is about 2.5×10^7 years. The mean cosmic ray density in the halo is calculated to be approximately an order of magnitude lower than near the earth. These particles eventually leak into extragalactic space, where they join similar particles from other nearby galaxies and diffuse with a density lower by perhaps another two orders of magnitude.

Particles in the range $10^{17} - 10^{20}$ eV cannot be confined to the spiral arms. Indeed protons at the highest energies cannot easily be confined within the total galactic sphere. These particles are considered to originate outside the galaxy, probably in extremely strong radio sources, and to diffuse throughout the local supercluster of galaxies. Following Burbidge[8], this is taken to have a mean radius of approximately 3×10^7 light years and to contain about 10^4 galaxies, perhaps 10 of which are currently strong radio sources. If the diffusion mean free path is taken as 10^5 light years for particles of these energies, they are confined

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to this space for approximately 10^{10} years. The energy spectrum with which these cosmic rays are injected into metagalactic space is at least as flat as that of cosmic rays observed in the range below 10^{15} ev ; indeed, the unusually flat radio spectra of some strong radio sources leads to speculation that the spectrum of cosmic rays from these sources may be correspondingly flatter.

Particles observed at the earth in the range $10^{15} - 10^{17}$ ev are taken to come from supernovae within the galaxy. However, they are too energetic to be confined easily within the spiral arms. As Syakov[9] has pointed out, the effective mean free path for protons above 10^{15} ev becomes longer than the 10 light years chosen. As the proton mean free path increases with energy, the storage life time goes down and the intensity of protons falls more rapidly than in the injection energy spectrum. However the Larmor radius for heavier nuclei of the same total energy varies as $\frac{1}{Z}$. This heavy cosmic rays will only experience a change of mean free path at higher energies than protons.

A significant percentage of the cosmic rays at total energy 10^{15} ev (as distinguished from the energy per nucleon) are believed to be alpha particles or heavier nuclei. Thus the kink in the primary energy spectrum at about 10^{15} ev reflects two related phenomena: a faster loss of high energy particles as the effective mean free path is increased with energy and a shift to heavier nuclei as this first effect is felt by protons at lower energies than by heavies.

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Some consequence of this model are listed below:

i. It produces an energy spectrum rather similar to that discussed by Linsley[1]. Particles in the range 10^{10} - 10^{15} eV reflect the energy spectrum with which they are produced in supernovae. This spectrum steepens in the range 10^{15} - 10^{17} eV as first protons and then heavier nuclei experience a longer diffusion mean free path. At about 10^{17} eV the intensity of such particles falls below that of cosmic rays diffusing in metagalactic space. Above 10^{17} eV the energy spectrum of cosmic rays reflects that with which they are produced outside our galaxy — probably in strong radio sources and quite possibly with a somewhat flatter spectrum than galactic cosmic rays.

ii. The cosmic ray density is higher in the spiral arms than in the galactic halo. It is still lower in extragalactic space. Thus the amount of energy given over in the Universe to cosmic radiation can be kept relatively low.

iii. The diffusion lifetimes within the spiral arms and the halo are calculated to be approximately 10^5 and 2×10^7 years. If the mass densities in these regions are taken to be approximately 10^{-24} and 10^{-26} gm./cm^3, respectively, typical cosmic rays in this space will have passed through less than 1 gm./cm^2 since injection from supernovae. Thus the observed abundances are explained as reflecting the composition of supernovae and spallation, etc., which occur during acceleration within the supernova sources.

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In the range 10^{15} - 10^{17} eV one expects the composition to shift markedly to heavies. This is consistent with McCusker's data rather than Zatsepin's. At energies above 10^{17} eV the primaries will be approximately 10^{10} years old. Therefore most heavy primaries will have decayed to protons as a result of interactions with intergalactic photons Doppler-shifted to energies over 10 MeV , as suggested by Morrison[7], Ginzburg[10], and others. This agrees with Linsley's observations.

At the present time, cosmic ray data seem to be consistent with the model above. It will be strenghened markedly by confirmation of the steepening of the energy spectrum at about 10^{15} eV and the flattening at about 10^{17} eV , and by confirmation that the primary abundances shift towards the heavies in the range 10^{15} - 10^{17} eV and change abruptly to protons at higher energies. It will be weakened appreciably if improved data disprove these suggestions. The model will similarly be strengthened if the energy spectrum continues beyond 10^{20} eV , and is shown to be somewhat flatter than below 10^{15} eV ; however, it does not demand these results, since it may be difficult to confine particles above 10^{20} eV even within a supercluster larger than 10^{7} light years in radius.

The author is grateful to the Department of Applied Mathematics and Theoretical Physics, University of Cambridge, for its hospitality while this work was done, and to Professor F. Hoyle and Dr. D. Sciama, among others, for stimulating conversations.

+ Work supported in part by the National Aeronautics and Space Administration under grant NSG 58-60.

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2. John Linsley and Livio Scarsi, Phys. Rev. Letter, 9, 123, (1962).

3. G.T. Zatsepin et al., Report at the International Conference on Cosmic Rays, Jaipur, (1963).

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5. Further details are given in a forthcoming paper. The author also has been told that similar ideas were discussed at Jaipur in December, 1963.

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9. V.H. Byakov, Soviet Astronomy - A.J., Vol. 7, No.4 (Jan-Feb, 1964 in English Translation).

10. V.L. Ginzburg and S.I. Syrovatsky, Prog. Theor. Phys. Suppl. 20 (1961). This paper refers to other Russian work on the subject.